Beam Dynamics in Induction Linacs*

Edward P. Lee

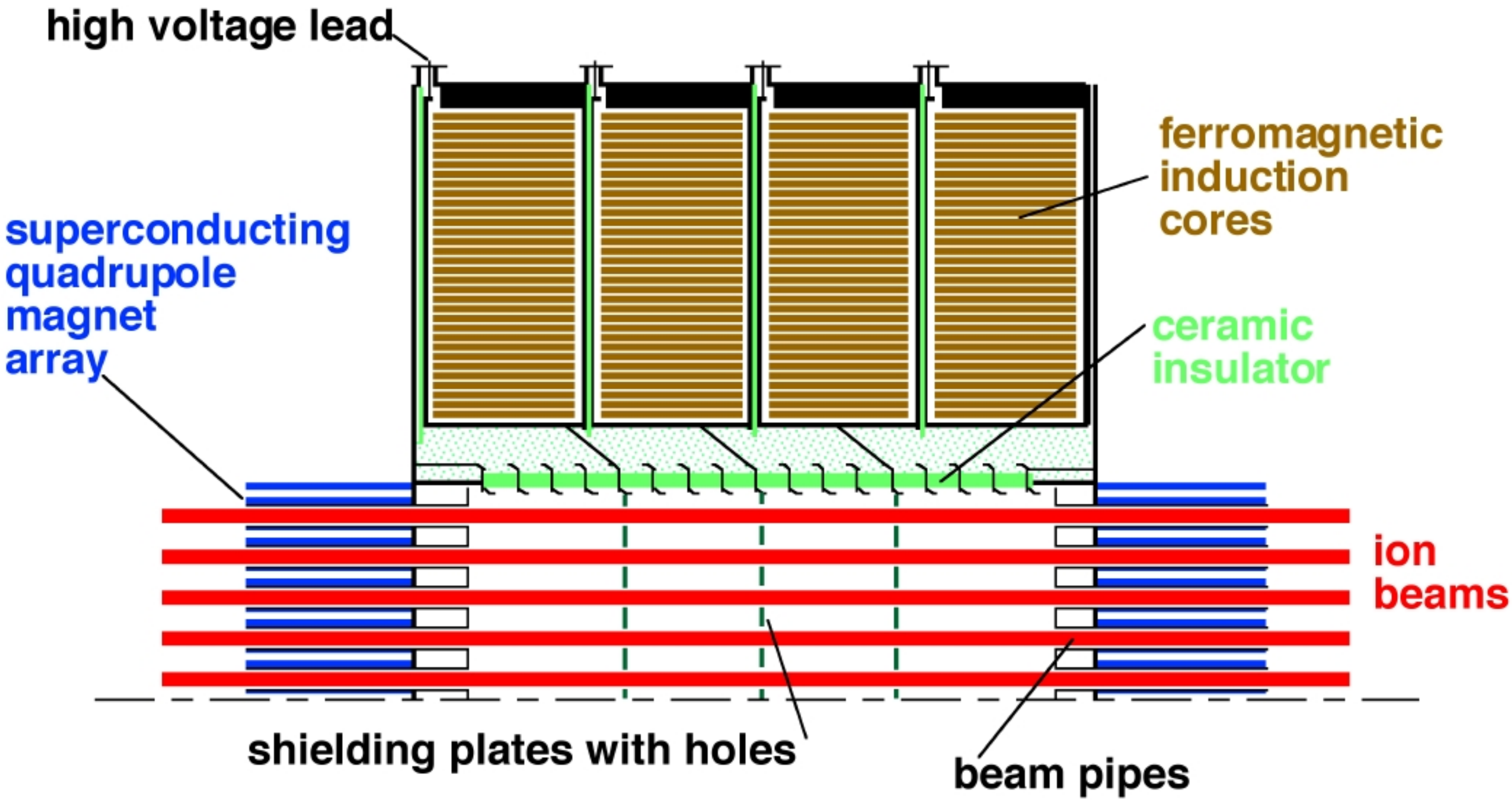
Lawrence Berkeley National Laboratory

Presented at HIF 2012
Berkeley, CA
August 14, 2012

Induction Linac Features
Beam Dynamics Overview
Choice of Transport Lattice
Longitudinal Stability

*This work was supported by the Director, Office of Science, Office of Fusion Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231

In a Heavy Ion Fusion driver, ~100 beams are accelerated in tandem through a series of induction cells



The beams interact with each other through EM fields: deflections, longitudinal inductive forces, and "loading" of the power source must be controlled.

Linear Induction Accelerators (LIA)

- Pulsed power ciruitry puts an electric field directly on an acceleration gap:

  Charge in capacitor $\rightarrow$ Switch $\rightarrow$ Field on gap
- An induction core temporarily prevents the short to ground

  Gap voltage x pulse duration = (Longitudinal core area) x (core flux swing)

  example: $200\text{kV} \times 1.0\mu\text{s} = .2\text{m}^2 \times 1.0\text{T}$
- Capacitor Energy $\rightarrow$ Beam + Core heat + Refection

- The beam's return current flows through the pulsed power circuitry and induces a reverse field in the gap
- If refected energy can be recovered in the capacitor electrical efficiency can be high, e.g. $\approx$50% for $I_{beam} \approx 1.0$kA

- Unlike an rf linac, the accelerator cavity/gap is not driven at a resonance. This allows for large aperture and high current, but with more complicated beam dynamics.
- The main experience so far:

Electron LIAs for radiography	DARHT	$\begin{cases} 20 \ \ \text{MeV} \\ 1.0 \ \ \text{kA} \end{cases}$
beam weapons	ATA	$\begin{cases} 50 \ \ \text{MeV} \\ 10 \ \ \text{kA} \end{cases}$
fel & misc	ETA	$\begin{cases} 5 \ \ \text{MeV} \\ 1.0 \ \ \text{kA} \end{cases}$
Ion LIAs for WDM	NDCX II	$\sim$ 1 MeV Li^+
and fusion exps.	MBE4	$\sim$ .4 MeV K^+

- Light Ion Fusion used pulsed power applied to a single or few gaps - very different from HIF (very high ion currents)

- Electron LIAs have used solenoids for transverse confinement. Longitudinal confinement is not needed because v = c.

- The main dynamical issue for electron LIAs has been the <u>Beam Breakup Instability</u> (BBU), a transverse hose-like motion driven by interaction with the accelerator modules

- Beam dynamics in HIF-LIAs is different from electron LIAs:

  BBU is probably not significant

  Transport is by magnetic quadrupoles, esp. for multiple beams

  Longitudinal control is a critical issue

  Beams must be very cold in both transverse and longitudinal directions (low emittance) to focus on target

<u>Accelerator Dynamics Design</u> (e.g. for HIDIX)

There is a formal procedure, but a reverse informal “rough design” proceeds it and must be sound:

“Formal” User Requirements → {Conceptual Design, Scientific Design} → Detail Design

(Community of users & designers, experiments, simulation, component developement) → Rough dynamical & component design → Iterate Etc. → Formal Procedure

End-to-end dynamical model needed:

- All known dynamical features included
- All known issues resolved
- Detailed component models for dynamics

This activity can guide research programs

Some dynamical considerations

Design of transport systems with multibeam interactions - halos?
Vacuum in acceleration gaps - 10^{-8} torr good enough?
Beam loss - activation, magnet operation, *e* cloud
Steering - all beams separately?
Alignment - all beams separately?
Diagnostics - all beams separately?
Longitudinal control - feed forward correction?
Source reliability - (for ~ 100 beams!)
Extra beams for reliability
Special operations - beam bending, splitting, combining
Electrical efficiency - special pulser circuits?
Magnet aberrations - emittance growth
Transverse/longitudinal coupling stable?
And more

All goes into an integrated end-to-end dynamical model.

LIA transport uses three types of focal elements

Magnetic quadrupoles (HIF driver)
Electrostatic quadrupoles (MBE4, HIF driver?)
Solenoids (NDCX II, electron LIA, HIF driver?)

Other types of focusing exist but should be minimized in the accelerator:

- electron clouds
- higher order multipoles
- weak focusing from bends
- beam - beam interaction
- reflection from pipe surface
- image charge and current effects
- magnet fringe fields

Accel/Decel focusing is also always present and is important in injectors

All of this goes into a dynamical model

Transport limit - simple model

$$\frac{d^2x}{dt^2} \approx -\omega_0^2 x + \frac{Ze}{\gamma M}\left(E_x - \upsilon B_y\right)$$ single ion transverse motion

Focal system

Space charge

$$\approx -\left(\omega_0^2 - \frac{Ze}{\gamma M}\frac{\rho}{2\varepsilon_0\gamma^2}\right)x$$

$$\rho \approx \frac{2\varepsilon_0\gamma^3 M}{Ze}\omega_0^2$$ for a very cold beam

Large ρ is a good figure of merit but there are other considerations:

line charge density per beamlet $\lambda \approx \rho\pi a^2$

Field limits, e.g.

$\mathrm{B} \leq 10T$

$E \leq 5\mathrm{MV}/m$

$\Phi \leq 100kV$

Stability: Phase advance per focal system period less than about 80°

Solenoid transport

In a reference frame rotating at the Larmor frequency $\left(-\omega_c/2\right)$:

$$\omega_0^2 = \left(\frac{\omega_c}{2}\right)^2 = \left(\frac{ZeB}{2\gamma M}\right)^2$$

$$\rho \approx \frac{2\varepsilon_0 \gamma^3 M}{Ze}\left(\frac{ZeB}{2\gamma M}\right)^2 = \frac{\varepsilon_0}{2}\frac{Ze\gamma}{M}\overline{B^2}$$

$$\lambda = \rho\pi a^2 = \left(10\frac{\mu C}{m}\right)\left(\frac{Z}{M/133amu}\right)\left(\frac{B}{10T}\right)^2\left(\frac{a}{10cm}\right)^2$$

This looks pretty good for large radius beams at low energy (< 100MeV), but it may not work for multiple beams.

Magnetic quadrupoles have a strong transverse field alternating in sign:

$$\vec{B} \approx \pm B' \quad \left(x\hat{e}_y + y\hat{e}_x\right)$$

For lattice period P with 50% magnet occupancy:

$$\omega_0^2 \approx \frac{\mathrm{P}^2}{96}\left(\frac{Ze}{\gamma M}\right)^2 B'^2$$

$$\rho \approx \frac{\varepsilon_0}{48}\frac{Ze\gamma}{M}\left(\mathrm{P}^2 B'^2\right)$$

Looks similar to solenoid but P can become large as ion energy Increases. Superconducting pole fields (in wire) may reach about 6T:

$$B_{pole} \approx 2B'a \leq 6T$$

Beam channels in multibeam arrays can share poles in an efficient design.

<u>Electrostatic quadrupoles</u> seem similar to magnetic quadrupoles; just substitute

$$B' \longrightarrow E'/\mathrm{v} \text{ transverse field gradient}$$

$$\rho \approx \frac{\varepsilon_0}{48}\frac{Ze\gamma}{M}\frac{\mathrm{P}^2 E'^2}{\upsilon^2} \qquad \text{(50\% occupancy)}$$

But the pole potential is limited by the multibeam geometry and high voltage feeds:

$$\Phi_{Pole} \approx 2a^2 E' \leq 100kV$$

Combined with the stability condition line charge density per beamlet is limited:

$$\lambda \leq \frac{1}{2}\frac{\mu C}{m} \qquad \text{(independent of Z, M, v)}$$

Longitudinal dynamical models are not well developed for high current ion beams

Simple mulitbeam model equations:

$$I = \lambda \upsilon$$

$$\frac{\partial I}{\partial t} + \frac{\partial \lambda}{\partial z} = 0$$

$$\frac{\partial \upsilon}{\partial t} + \upsilon \frac{\partial \upsilon}{\partial z} = \frac{Ze}{\gamma^3 M}\left(\mathrm{E}_0 + \mathrm{E}_I - g\frac{\partial \lambda}{\partial z}\right)$$

The field induced by return current (-I) has been approximated using a circuit equation:

$$-\mathrm{E}_I = \underbrace{RI + L\frac{\partial I}{\partial t}}_{\text{destabilizing}} + \underset{\text{stabilizing}}{\frac{1}{C}\int^t I(t')}$$

The space charge force $\left(\sim \partial\lambda / \partial Z\right)$ is stabilizing.

- At low frequencies (~10 MH_z) the circuit parameters are related to pulser design and electrical efficiency.
- High frequency values (~100MH_z) may have different circuit parameters (module design).
- Unstable (e-fold) distances ~ 100m have previously been calculated. Feed-forward correction may be a solution.
- Spread $\Delta P/P \sim 10^{-2}$ may stabilize but this is too large for final focus.
- Multiple beam effects probably important at high frequency.
- Other modes may be excited.
- Renewed study and a good pulser/module model are desirable.